Analyze the Potential of Use Thermoelectric Materials for Power Cogeneration by Energy Harvesting - Brazil

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Abstract

Thermoelectric materials have a physical behavior that enables the generation of energy. Therefore, this research aims at the formation and consolidation of knowledge about thermoelectric materials and their application of energy harvesting for cogeneration. Two laboratory experiments in this paper have been carried out to demonstrate the potential of this source of energy cogeneration. First of all, the simulation of the application of thermoelectric module in high temperature gradients was made and then the thermoelectric module was applied in a processor in the second experiment operation. The application processor provided unsatisfactory results due to the low temperature gradient. While the laboratory simulation, due to the high temperature gradient, gained desirable results for use in energy harvesting of the industrial processes. The Brazilian Potential for cogeneration of electricity, how Brazil consumes electricity in a year and how much would be possible to save have been examined if the thermoelectric modules were used in the ceramics industry, new cars and airplanes. The result was extremely promising, resulting from the potential vehicles combustion. Furthermore, the cogeneration using thermoelectric modules is totally clean, avoiding the emission of carbon to the environment.

Keywords

Energy Harvesting, Thermoelectric Module, Source Energy and Green Energy.

Introduction

The proposed research is to verify the behavior of thermoelectric modules for development of a system for energy harvesting. Thermoelectric materials are materials capable to convert temperature gradient directly into electricity through the Seebeck effect. Among the various possibilities of harvesting energy, the use of thermoelectric materials is our priority, because the modules require a small footprint, and have no vibration or noise during operation. Since recent studies concerning rare earth development of new materials have showed that the thermoelectric modules can reach yields close to 20% (Nascimento A. et al, 2012).

Thermoeletric Materials

The thermoelectricity relates temperature and electricity. The Seebeck effect, discovered by Thomas Seebeck Johann, generates a potential difference between two bimetallic joints at different temperatures (Campos D. N., 2011).

Later a physicist named Jean Charles Athanase Peltier discovered that a metal junction can produce heat or cold, the reverse process of Seebeck.

Thermoelectric materials are derived from semiconductors, with a higher current density and therefore, the power, due to their proportionality. The semiconductor materials most used are tellurium, antimony, germanium and silver, highly doped semiconductors to create n-type and p-type grouped as pairs which act as dissimilar conductors.

Thermoeletric Modules

Conventional thermoelectric modules with various specifications according to the application, whose dimensions are varied and tracks to the heat rate may vary from 1 Watt to 125 Watts, with studies underway that may increase this range. The temperature gradient between the hot side and the cold side can reach up to 200°C, are mostly composed of 3 to 127 thermocouples distributed in some applications operating in cascade in series in order to obtain greater differences in temperatures, which can reach about 250°C. Temperatures reached can also be negative, which could arrive experimentally at -100°C (Souza D. H., 2007).

Power Generation

Among applications on an industrial scale stands for use by NASA of a micro thermoelectric material in space, the spacecraft like Voyager, Pioneer, Galileo, Cassini, and Viking (Nascimento A. et al, 2012).

FIG. 1 SATELITE VOYAGER [5]

Presently there are studies using thermoelectric modules in cars whose combustion engines have a maximum yield of 33%, and thermal losses (heat dissipation and exhaust gases) are at least 57% (G.Min, 2011).

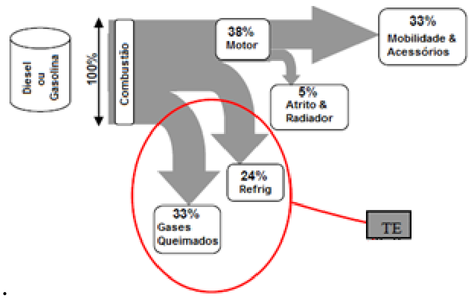

FIG. 2 USING THERMOELECTRIC MODULES IN CARS (G.Min,2011)

Given that only 33% of combustion is converted into work, or 57% will be lost (33% burned gases and 24% of the losses are cooling). the temperature gradient is supposed, it is possible to grasp about 5% (yield of the module), an increase in the yield of 8.67% in the automobile.

Mathematical Modeling

Mathematical modeling is the representation of heat transfer from the module flowing to the environment, characterizing each step of this transfer. Models of heat transfer occur simultaneously, being these models, conduction, convection and radiation, may examine each of these separately.

The heat conduction is the phenomenon that occurs between solids that expose themselves to different temperatures and in contact one to another. Equation (4) describes what is used as the Fourier fundamental equation when their analytical theory of heat is investigated, with the rate of heat transfer conduction through. It is important to note that radiation also takes place between solids, but it is very difficult to separate them from the pores of the solid (Souza D. H., 2007).

$$Qcond = kA\frac{\Delta T}{L} \text{ [cal]} \tag{4}$$

Where:

k: thermal conductivity of the material

A [M²]: Contact area

$\frac{\Delta T}{L}$ [°C/M]: Temperature distribution

The exchange of heat with the surroundings takes place through conduction and convection models and also in a way inferior to the other resultant from radiation. Not being considered possible heat exchange with ventilators that cool the thermoelectric module. The heat exchanged by convection occurs according to Newton's Law of Cooling, known by (5) below.

$$Qconv = hA(Ts - T\infty) \text{ [cal]} \tag{5}$$

Where:

h [W/M²K]: Convection coefficient

Ts [K]: Surface temperature

$T\infty$ [K]: Ambient temperature

Energy balance for thermoelectric module

The energy balance is related to the rate of heat absorbed, with the input power and the amount of heat dissipated (Souza D. H., 2007). Therefore, the amount of heat dissipated is:

$$Qh = Qc + Pin \text{ [cal]} \tag{6}$$

Where:
Qh [cal]: Heat dissipated
Qc [cal]: Heat absorbed
P*in* [W]: Power input
Given that the process related to thermoelectric effect, requires the inclusion of the thermoelectric effect on energy balance Qc, the material properties are independent of temperature, and half of the heat is generated by Joule effect.
According Moretto, for the Joule effect the best performance of the module occurs in each plate form equal to half the total effect of the module, as well as to transfer heat that is induced by temperature gradient appears between plates (Souza D. H., 2007). Thus it appears as (7).

$$Qc = 2N\left(\alpha ITc - I^2\frac{R}{2}\right) - k(Th - Tc)\ \text{[cal]} \qquad (7)$$

Where:
N: Number of thermocouples module
α : Seebeck coefficient of the material
k: Conductivity of the material
T*h* [°C]: Hot side temperature
Tc [°C]: Cold side temperature
By comparing (10) to (11), one can verify the possibility of expanding pin expressed in (8).

$$RI^2real = \frac{RI^2otm}{\eta} \quad \text{[W]} \qquad (11)$$

For simlification, it can be described as (12).

$$Ireal = \frac{Iotm}{\sqrt{\eta}} \quad \text{[A]} \qquad (12)$$

The coefficient of cooling performance, or COP value is demonstrated in (9), which means how many times the amount of cooling that is greater heat absorption by the cold side (Souza D. H., 2007).

Calculation of Efficiency

To analyze the behavior of the yield of a thermoelectric module, there are some steps to follow. The calculation procedure for studied work is based on the Seebeck technology from a thermal load and a temperature gradient, determining satisfactory operation points, and estimating the performance for the system, since this presents no linear behavior (Campos D. N., 2011).

The electrical and thermal characteristics by graphic analysis of the performance of thermoelectric materials to be used are extracted from the datasheet model TEHP1-1.2-24156 available for the manufacturer and shown in Figure 7 with the intention to exemplify the calculations. It is noteworthy that for each application various types and combinations of modules should be analyzed in order to obtain the best result for the system.

Together with the data from the module working temperature, the thermal load of the system is determined, and may be of two designs. The active thermal load is to be the thermal energy dissipated by the device. And the passive heat load is derived from the radiation, convection or conduction, or a combination of the last two (Souza D. H., 2007).

The performance of the module is estimated, using the relation Dt / ΔTmax, expressed as below:

$$\frac{\Delta T}{\Delta T\max} \qquad (13)$$

The technical data of the thermoelectric material relationship with the current temperature gradient has been analyzedand covered the ratio I/Imax. With the current value of the ratio by the maximum current allowed by the material, the operating current of the module is.

$$\frac{I}{\mathrm{Im}ax} = X \qquad (14)$$

Where, X: value extracted from the graph.

The voltage limit specifications for the thermal load are obtained from I x V curve of the device, using the current value found previously. With the results of operating voltage and current, the calculation of power generated is made.

$$P = V \cdot I \quad \text{[W]} \qquad (15)$$

Therefore, there has knowledge of the theoretical values required for analysis of the behavior of thermoelectric material (Souza D. H., 2007).

Correspondent Electric of Generation Thermoelectric

The use of the thermoelectric module to convert energy becomes a form of power generation uncontrolled, not being thus possible to measure all that energy from the waste heat and thus maximum energy transfer has been obtained.
Therefore, an efficient cogeneration system consists of various auxiliary equipment. The main components that make up the thermal cogeneration system are:

- Hot Source: Source of waste heat.
- Thermoelectric Module
- Cold Source.

- DC Converter - DC: Filter level.
- Charge Controller: Adjusts load protecting against overloads.

It is noted that the use of thermoelectric modules for power generation is not only limited to the module, but a set of electrical equipment that makes a structure be a single result (Rahman M., Shuttleworth R., 1995)

Experimental Analysis

Theoretical Analysis of Thermoelectric Modules

A thermoelectric module utilizes INBC1-127.0HTS manufacturer WAtronix Inc., whose dimensions are shown in Fig 3 (L. Watronix, 2008).

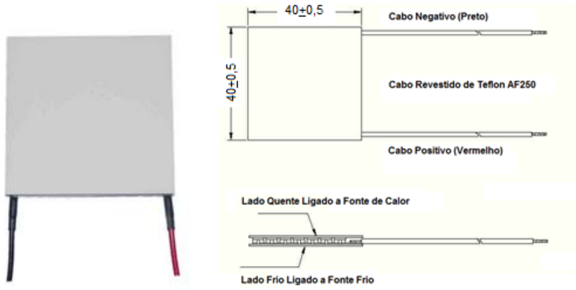

FIG. 3 THERMOELETRIC MODULE MODEL INBC1-127.0HTS (L.Watronix, 2008)

The behavior of the thermoelectric module is shown in the graph of Figure 4, and it is possible to analyze which values of power, voltage and current are in relation to temperature gradient

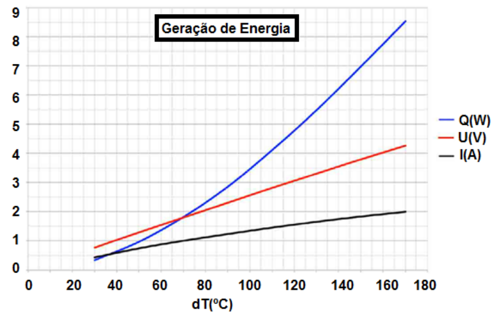

FIG. 4 CURVE OF THE PERFORMANCES INBC1-127.0HTS (L.Watronix, 2008)

Analysis of the experimental model on thermoelectric module TEHP1-24156-1.2 manufacturer Thermonamic Module (Fig. 5) has been performed. The module that uses Bismuth and Tellurium thermoelectric (Bi-Te) and can work at elevated temperatures of up to 330◦C, is coated with graphite sheet of high thermal conductivity, without requirement for application of thermal greases (M. Thermonamic, 2012). Based on the theoretical study, the experiment was developed to simulate the temperature gradient and after analyzing the behavior of thermoelectric modules. To perform the experiment, two models are used, INBC1-127.0HTS and TEHP1-24156-1.2, and conducted on both separately.

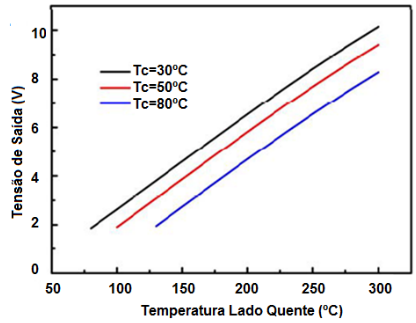

FIG. 5 CURVE OF THE PERFORMANCES TEHP1-24156-1.2 (M.THERMONAMIC, 2012)

Initially, the calculations were performed to analyze the performance of thermoelectric modules, followed by calculation of income shown in mathematical modelling to the module INBC1-127.0HTS with the values: R = 2Ω and P = 16W. As for the thermoelectric module model TEHP1-24156-1.2, I = A and P = 11.6 W. 60.32 have been acquired.

Knowing thus the theoretical values to analyz the behavior of a thermoelectric module of each of the two available models to be applied, it is possible to consider such values higher than that shown in the manufacturer's data sheets, with a maximum output of 8.5 watts for model INBC1-127.0HTS and 20 watts TEHP1-24156-1.2. The theoretical values of thermal efficiency for modules INBC1-127.0HTS and TEHP1-24156-1.2 are 60.32 W and 16W respectively.

To perform the experiment, was placed on a stove with a metal plate of thickness approximately 20 mm and on top of this plate the four thermoelectric modules were placed distributed side by side on the same. On the other side of the modules is placed a heat sink was placed coupled to a metal box, with dissipation fins inside this box. The housing came with an opening in its top so that it can be placed within this coolant in order to obtain a greater temperature gradient. Fig. 6 shows an image of the experiment.

FIG. 6 IMAGE OF THE EXPERIMENT

The realization of measurements involved in

thermocouples for temperature measurement, two thermocouples being placed on the warm side and two on the cold side of the experiment. To carries out the measurement, voltage of thermoelectric modules was evaluated. Given that the experiment will be performed without charge, the values of current and power output were discarded. For this measurement, the voltage utilized a multimeter. Measurements were performed on each module individually.

When the modules were connected either in series to the increasing output voltage, or in parallel, the current was larger than the limit that modules could hold. The modules can also be associated in parallel thermally, one over another, and thus a higher output power was gained.

In Fig. 7 it is possible to observe a thermographic image taken from experimental and simulation in Fig. 8 shows the values collected in behavior analysis module in the experimental analysis.

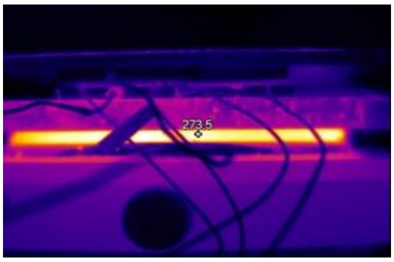

FIG. 7 ANALYSIS OF THERMAL OF THE SYSTEM

After analyzing the behavior of thermoelectric modules in the system, we performed load application. This in turn presents a resistance of 6 Ω.

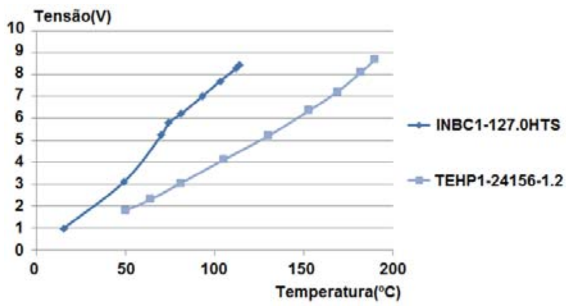

FIG. 8 SHOWS VOLTAGE RESULT THAT OCCUR AT INCREASED TEMPERATURE.

The chart of Fig. 8, generated by the results, shows that increased temperature gradient occurred, it has therefore a higher output voltage at the load.

In Fig. 9 there are power values supplied by the modules INBC1-127.0HTS and TEHP1-24156-1.2. The chart of Fig. 9, generated by the results shows that increased temperature gradient occurs, it has therefore a higher power supplied to the load by the thermoelectric module.

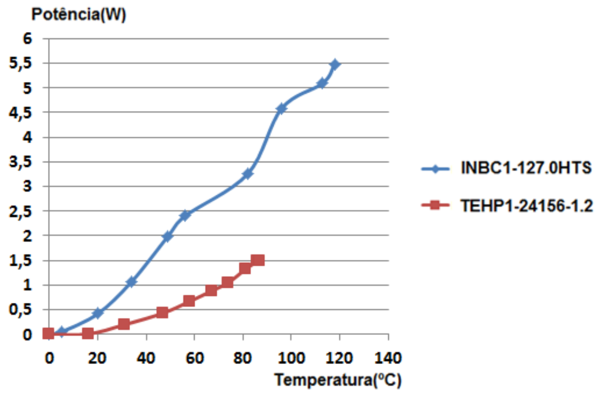

FIG. 9 SHOWS ENERGY RESULT THAT OCCUR AT INCREASED TEMPERATURE

Microcomputer Application

The calculations to understand the performance of the modules have been initially implemented, follpwed by the acquisition of the values I = 1.4 A and P = 1.82 W. As to the thermoelectric modules TEHP1-24156-1.2 using the same calculation procedure, the following results were: A I = 2.32 and P = 7.19 W. The theoretical values used to investigate the behavior of a thermoelectric module of the two models available have been well known.

Due to the dimensions of 35.1 x35 processor, 1 mm and thermoelectric modules available for the experiment module thermoelectric model INBC1-127.0HTS was applied in the experiment by the presence of cohesion along with the processor. The thermoelectric module processorwas jointed to the wall of the hot source module. The values obtained for the thermal efficiency modules INBC1-127.0HTS and TEHP1-24156-1.2 were 1.82 W and 7.19 W respectively. On the wall of the cold source of the thermoelectric module, heat sink was attached, being the source cold (room temperature). The application module at this location did not affect the performance of computer processing. The amounts collected in the analysis of thermal processor are shown in Fig. 10.

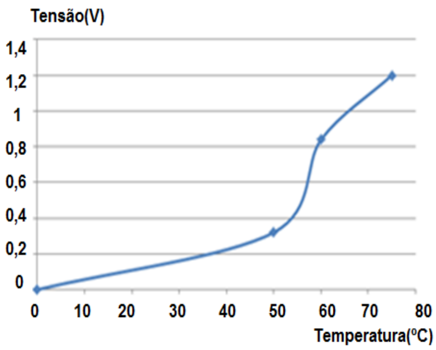

FIG. 10 ANALYSIS OF THERMAL PROCESSOR

It has been observed in Fig. 10 that as the processing rate of temperature change is the processor, in consequence of which the heat sink temperature has risen.

Therefore, it is perceived that the power generated increases proportionately with the processing rate, i.e the greater the processor utilization is, the higher the temperature dissipatedis.

The Fig. 11 shows a thermographic image processor temperature.

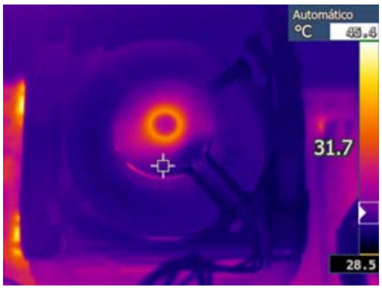

FIG. 11 THERMOGRAPHIC IMAGE PROCESSOR TEMPERATURE

In the chart of Fig. 10 it can be seen that with increasing processing rate temperature gradient and thus a higher output voltage are increasing.

Analysis of Results

By analyzing the theoretical results found in the experiments, such as 1.2 Volts in the application of thermoelectric module INBC1 127.0HTS-in microcomputer, and 8.65 Volts on the analysis of experiment , a great difference between the two case studies has been observed, where the levels of temperatures reflect the values of the discrepancies.

The amounts collected and presented in Fig. 10 where it has a value of 1.2 Volts for a temperature gradient of 40◦C show a very low yield, with the primary cause instability of the temperature gradient, showing variations of values due the processing fee that undergoes variation as a function of their use, however, it has become a stress response. This application is difficult, because the voltage found is very limited and unstable, with the consequence that the need to operate the processor 100%, which does not occur continuously, since this degree of processing all the time is excluded from usage. If the voltage is stable, application would be restricted, however ,one could use location.

In laboratory simulation of application of thermoelectric modules for temperature gradients elevated responses are shown in Fig. 8, which demonstrates superior performance to study the microcomputer. The thermoelectric module is allocated with his face close to hot exhaust and cold along with your face cooling, so a temperature difference occurs. With the aid of measuring equipment, energy from a source residual is generated. Tensions at levels of 8.69 V responses have been found, with such satisfactory results.

It is noteworthy that strains of 8.69 Volts feeds are values applicable at various levels of signals present in automobiles as well as battery chargers, thus justifying possible utilizations. Fig. 9 shows graphically the power consumed by a load of 6 ohms, and can reach levels of 5.5 watts, which confirms the micro power.

Overall the results are desirable, proving that it is possible to generate power through the use of thermoelectric materials. The different responses provided between the application module and the microcomputer simulation occurs primarily by the temperature gradient obtained in each test.

Analysis of the Potential for Cogeneration - Brazil

According to the capabilities and limitations of current technology of thermoelectricity and the knowledge on the advantages and efficiency of thermoelectric modules, this stage of the work will compute how much energy can be saved with their application in some systems. The calculations involve the Brazilian national scene, and comparisons are made in order to facilitate the interpretation of the final values obtained.

Ceramics Industry

In industrial processes, the Brazilian industrial consumption in 2012 was 62.89 TWh (Agencia Nacional de Energia Elétrica, 2013), and 1,348 GWh is consumed by the ceramic (MME, 2009). It is estimated that only about 3% of all domestic industries joined the use of cogeneration system thermal and considering the increased yield of the aviation industry 0.5%, which is easily achievable. The potential annual savings of electricity would be 9.43 GWh. The application of factor estimated at only 3% in the ceramic industry indicates that the capture system generates savings of 202.2 MWh / year.

If 100% of uses cogeneration systems industries the economy would reach 314 GWh. Knowing that each Brazilian consumes on average 2400 kWh/year of electricity (Gandra A., 2013), the value previously found would be enough to supply a city with over 131,000 inhabitants.

Fleet Car Ride

In the last decade, the number of vehicles in the

country nearly doubled and as presented in the previous chapters vehicle efficiency combustion is less than 33%. It has been confirmed that there will be studies on application of thermoelectric modules for cars with the goal to captur the thermal losses for power generation in order to raise the efficiency of the overall system.

Consequently, an analysis can be performed to discern the market potential for the reduction of fuel consumption by capturing residual energies, using the thermoelectricity.

To carry out this analysis a survey on the number of vehicles is made, for the purpose of emphasis on the amount of fuel to be saved feasible, with reuse of the thermal energy of the exhaust system of the automobile.

The fleet of cars in Brazil in December 2012 was 42,682,111 during the same period in 2011 totaled 39,832,919 the same cars (DENATRAN, 2013). Since the number of cars was increased by 7.15% in one year period, as shown in Fig. 12.

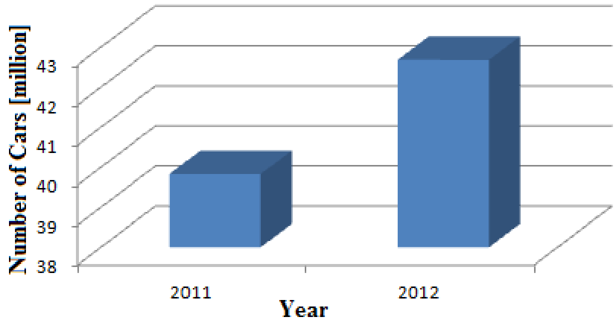

FIG. 12 BRAZILIAN CAR FLEET

Considering that in December 2013 the percentage increase fleet is maintained, there will be 3,051,770 new vehicles in Brazil. Since the average fuel consumption equivalent tonnes of carbon is 1.4 toe/year [15]. Thus consumption expected to increase the fleet of vehicles will be 4,272,478 toe / year.

Currently, thermoelectric materials have an efficiency of 3 to 7%. Therefore, it is possible to capture thermal losses of 5% of a vehicle in and around 57% of all fuel that is consumed by the car. This can be used for cogeneration of energy through thermoelectric corresponding to 2.85% of total heat loss. As it is well known that the maximum theoretical yield of a combustion engine is 33% (burning fuel), a relationship is made to know the total percentage that fail to spend, i.e, the real value of savings is of 8.64%.

Thus, if every new car that emerge in 2013 is equipped with thermoelectric microgenerator, the economy in this period will be 369,142 toewhich is more than the consumption of all cars in the city Florianópolis - SC in 2012, and meanwhile, at the end of the year 198,705 vehicles had been acquired (DENATRAN, 2013), multiplied by the average consumption of each car (1.4) , amount to 278,187 toe/year.

Commercial Aviation

Fuel consumption by the Brazilian aeronautics industry is considerably high. The Brazil in 2012 has consumed 7292 billion liters of jet fuel-jet fuel compared to 6955 billion liters in 2011 which obtained an increase 4.8%, or 337 million liters (ANP, 2012). This increase can be seen in Fig. 13.

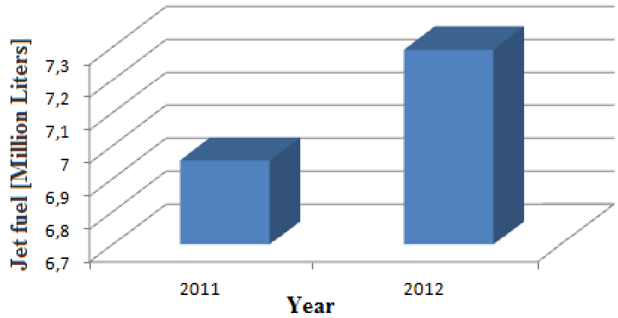

FIG. 13 JET FUEL CONSUMPTION IN BRAZIL

Based on the data in Fig. 13 an analysis on the amount of fuel which can be saved in one year in Brazil is performed. The increase in annual consumption of kerosene is due to the increase of Brazilian air traffic, and consequently with the emergence of new aircraft.

Considering that every new plane could be equipped with thermoelectric microgenerators capable to reduce by 0.5% kerosene consumption (HUANG J., 2009). Then, with an annual increase of 337 million liters of jet fuel, 1,685,000 gallons of jet fuel could be saved a year.

The Boeing 737-800 consumes in 1 hour flight from an average of 2970 liters of aviation fuel (www.portalbrasil.net/aviacao_comparativo.htm), and has a top speed of 840 km/h. Taking into account the economy jet fuel previously found, it has been that traverse this plane could travel 567 425,505 km traverse, meaning more than 10 times around the earth, since it has a length approximately 40.000 km (CBNF, 2012).

Conclusions

Based on the results presented in this article, it is clear that cogeneration power using thermoelectric modules

is a promising source and presents results that are technically feasible for large scale use. The results are very significant, considering that only a few systems analyzed in this model can be applied to cogeneration.

It is worth noting that there are ongoing research aimed at improving the efficiency of thermoelectric materials, as well the need to use renewable sources is increasing, making cogeneration energy capture waste energy becomes an attractive alternative for industries.

It has been emphasized that there are other industries with great potential to capture residual energies for energy cogeneration, among which are the power plants (8.5% of national power generation) processes, foundries and potteries, and particularly the fleet of buses and trucks.

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